Masonry Enclosure Walls: Lessons learnt from the recent Abruzzo Earthquake

R. Vicente, H. Rodrigues, A. Costa
University of Aveiro, Portugal

H. Varum
University of Aveiro, Portugal
ELSA, Joint Research Centre, Italy

J.A.R Mendes da Silva
University of Aveiro, Portugal

ABSTRACT:
This paper approaches the issue of performance requirements and construction criteria for masonry enclosure and infill walls. Vertical building enclosures in European countries include, very often, non-loadbearing masonry walls, using horizontally hollowed clay bricks. These walls are generally supported and confined by a reinforced concrete frame structure of columns, beams or slabs. Since these walls are commonly considered to be non-structural elements, and their influence over the structural response is ignored, their consideration in the design of structures as well as its linkage to the surrounding structure is often negligent or insufficiently detailed. In consequence, non-structural elements, as for wall enclosures, are relatively sensitive to drift and acceleration demands when buildings are subjected to seismic actions. Many international standards and technical documents alert to the need of acceptability criteria for non-structural walls, however they do not specifically indicate how to prevent collapse and severe cracking and how to enhance the overall stability for severe seismic loading. In this paper, appropriate measures are proposed to improve both in-plane and out-of-plane integrity and the performance behaviour under seismic actions of external leaf of double leaf cavity walls as well as premature disintegration of the infill walls.

Keywords: Masonry enclosure walls, infill walls, in-plane, out-of-plane, cracking, performance improvement.

1. INTRODUCTION

1.1 Scope

Non-structural elements such as masonry infills and enclosure walls, parapets, balconies, chimneys etc., as well as lifelines suffer distortions and deformations, or can fall and compromise human life and serviceability and functionality of the building itself. The Loma Prieta (1989) and Northridge (1994) are good examples of the economical costs associated to non-structural damage (30 million USD dollars), even in buildings that were not so affected structurally. External masonry walls over all Europe have changed a great deal in the last decade, in consequence of new goals and challenges related with thermal performance and condensation control. One of the most contradictory measures on this matter is the external thermal bridge correction using traditional hollowed clay bricks. This technique has lead to the improvement of thermal behaviour, but also to some constructive risks, which lead to consequent defects and insufficient performance requirements when subjected to seismic action. One of the most common causes for the instability and poor behaviour of masonry enclosure and infill walls when subjected to seismic motions is the reduced support-width of the walls on the concrete slabs or beams. This reduced wall support is normally required to minimize thermal bridge effects over internal surfaces, such as mould growth and condensations (internal and external). With this procedure, designers intent to cover the concrete structure externally with a thin clay brick slip (normally half width of clay brick) that increases, locally, the thermal resistance.

2. MASONRY INFILLS AND ENCLOSURE WALLS

2.1 Thermal bridge correction

The major cause for the cracking and instability problems observed in several buildings is the reduced width of the support of the walls on the floor slabs or beams. This situation leads to high local stresses which effects are increased by brick internal geometry [Hendry *et al.*, 1997]. In this case, cracking can be dramatic, even for very low loads, depending on different support conditions. Work developed by Vicente and Mendes da Silva [2006] reports an experimental and numerical work on first cracking and final failure of hollow clay brick walls, with different support conditions. Using clay brick wall samples, cracking, resistance and collapse, under vertical centred and eccentric compression loads, with full and partial concrete supports, steel shelf angles supports and heterogeneous mixed supports (brick and concrete) was thoroughly studied.

To achieve the requirements of the new thermal codes throughout Europe, in what concerns the need to increase thermal resistance over concrete members, designers and contractors adopted several methods, based on a quite inconsistent and unknown technology (see Fig. 2.1). Among these methods it is more relevant a particular one that promotes an external overhanging of masonry walls 50–80 mm, outwards of the structure surface, that assures an external protection of the concrete members, increasing thermal resistance, and also preserves the alignment and the aspect of the facade. These less and poorly-supported walls are severely cracking and, in worse cases, fall apart. External solid or perforated clay brick walls are well known by building science and they are correctly built in many countries. However, the problem is different when brick resistance is very low and the percentage of horizontal voids is more than 60%, delimited by thin clay septums of 8–9 mm thick.

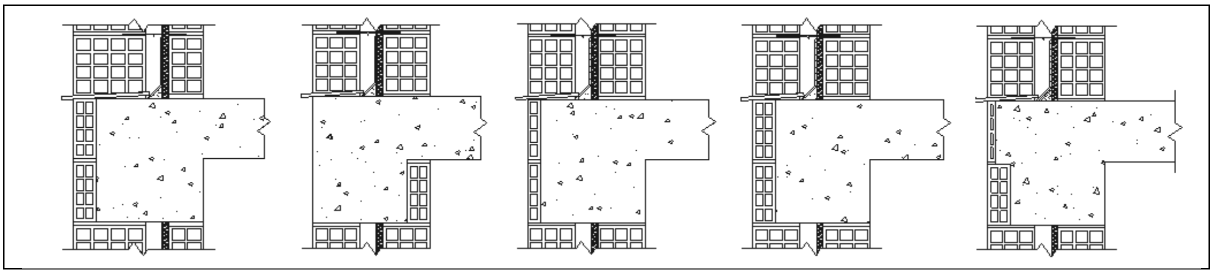

Figure 2.1. Typical thermal bridge correction schemes

Unfortunately, this method is frequently adopted without proper detailing for wall tying and without an accurate evaluation of brick resistance and masonry deformation. Fig. 2.2 shows two case studies where severe cracking occurred, imposing, in the first situation, the demolition and re-construction of the external leaf of the wall.

Figure 2.2. Two examples of severe mechanical defects resulting from inadequate correction of thermal bridges, using masonry walls partially supported

Other factors, beyond seismic action can also contribute to aggravate consequences, such as: excessive weight of exterior rendering, additional and eccentric loads, wind loads, creep and shrinkage movements of the structure, heat and moisture movements of the masonry, lack of wall ties, lack of technological knowledge and poor workmanship skills (particularly at singular points).

2.2 Contribution of the infill masonry panels in the seismic behaviour of RC buildings

The infill masonry panels are commonly used in the reinforced concrete (RC) structures as interior or exterior partition walls. They are not considered structural elements, however it is recognized the influence in the global behaviour of RC frames subjected to earthquake loadings [Crisafulli *et al.*, 2000]. Along the years many authors have study the effects of the infill masonry panels in the response of the RC structures and the need for including the infill masonry panels in the RC frames has been recognized [Rodrigues *et al.*, 2009]. The infill masonry panels if properly distributed and considered in the design of new structures can have a beneficial effect, or the negative effects associated with the irregularities introduced can be considered in the design process [Varum, 2003]. For the existent building, in particular RC buildings constructed before the 1980s that have deficient seismic behaviour according with the current knowledge can be considered a major source of risk for loss of human life and property.

As stated before, the masonry infill panels can have a significant contribution over the behaviour of RC buildings, however interaction between the masonry infill panel and the surrounding RC elements is complex, and because of this fact masonry infill panels are frequently neglected in the design or the assessment of existent structures. Ignoring the infill masonry panels can lead to important inaccuracies in the evaluation of the structural response, masonry infill panels change stiffness, strength, energy dissipation of the global structure and can induce local mechanisms not predicted with the models without the consideration of the masonry infill panels. From the analysis of the severely damaged or collapsed of RC buildings in recent earthquakes, it's clear that part of the damages can be associated with the structural modification to the basic structural system induced by the non-structural masonry partitions.

Considering the structural severe damage or collapse of RC buildings observed in recent earthquakes two principal mechanisms have been documented. The first associated with cases where masonry infill walls leave a short portion of the column clear, creating a short column, this situation is created by openings in the infill walls, for doors or windows, or for landing slabs of staircases. If in the design this effect was not considered, the short column with increased stiffness will be subjected to a high level of shear force and can lead to shear failure of the column. Secondly, the absence of the infill masonry panels in one storey, frequently in the ground floor storey due to the use of the storey for car parking or commercial use, induces a sudden change of the storey stiffness in height leading to a potential global soft-storey mechanism. Moreover the asymmetric distribution of the infill masonry panels can introduce torsion phenomenon's not predicted in the design, this fact can introduce additional forces not considered, especially in concrete columns of the outer frames [Fardis, 2006].

The infill masonry panels introduces significant changes in the structural behaviour of RC buildings, and can bring a beneficial contribution for the structural safety or lead to unexpected damage or collapse of the RC buildings, as so, the infill masonry panels contribution and participation in the seismic behaviour of RC buildings must be considered in the design of new structures and assessment of the existent building stock.

3. ABRUZZO EARTHQUAKE

3.1 Damaged masonry enclosure walls

In the recent Abruzzo earthquake, in Italy, particularly in the city of Aquila on the 6th of April of 2009, a widespread of non-structural damage was observed, mainly the out-of-plane collapse of the outer leaf of double leaf cavity walls. The Abruzzo earthquake hit several villages with different intensities; the maximum acceleration registered was 0.675g, widely exceeding the 0.25g defined in the design code. Within the reconnaissance mission, it was observed a group of systematic problems, consequence of bad construction practice.

Fig 3.1 shows non-structural damage of masonry enclosure walls of a six storey concrete framed building after the earthquake. Possible causes that lead to this level of damage are related to suscepyability of the balconies to higher vertical accelerations, slenderness of the masonry leafs, unconfinement of the external leaf, and the lack of ties or anchoring systems either to the inner leaf or structural concrete frame. In Fig 3.1 is also evident the existence of thin brick slips with deficient adhesion to the concrete beams and insufficient width support of the outer leaf (perforated brick) over the slab/beam.

Figure 3.1. Cracking and collapse of the outer leaf of a double leaf wall

In Fig 3.2 is shown the extensive disconnection of the veneer wall due to the lack of wall ties and insulation fixing system to the moment frame resisting structure.

Figure 3.2. The total disconnection of the outer veneer cladding wall

In both cases it is visible the inadequate mortar jointing of brick wall, being unfortunately a common practice associated to very poor workmanship.

Figure 3.3. The total disconnection of the outer veneer cladding wall

Slender walls are very sensitive to acceleration and displacement and conditioned to pheripherical connection and support conditions to the concrete frame structure, as well as the connection efficiency to inner leaves and orthogonal walls (see Fig 3.4).

Due to these aspects an out-of-plane mechanism can occur. However this mechanism can occur for lower levels of acceleration if previous in-plane damage is inflicted over the wall as reported in Fig 3.3.

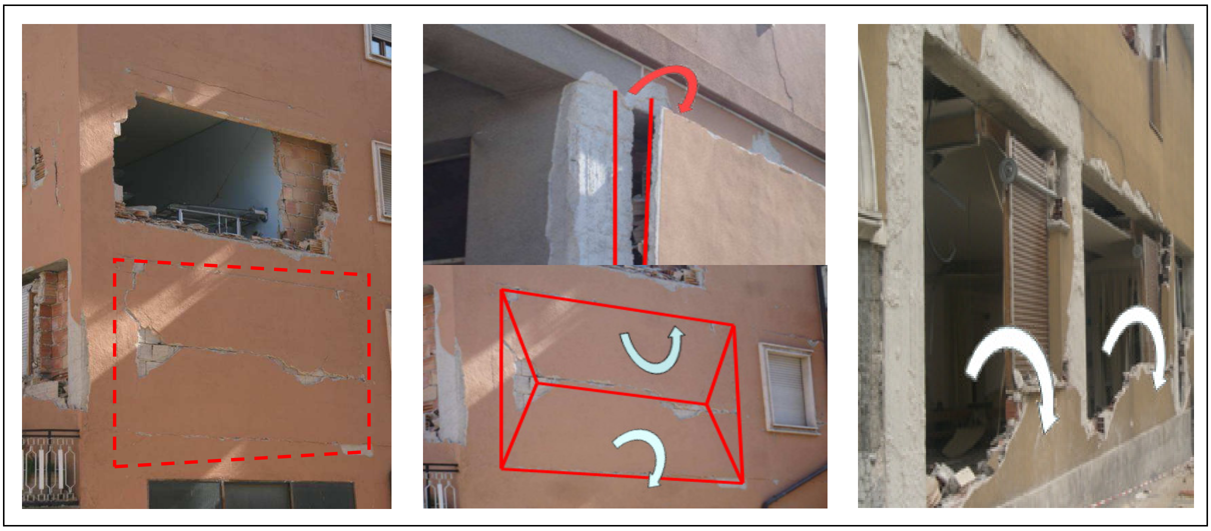

Figure 3.4. Out of plane collapse of infill walls

Unconfined masonry panels, disproved of no vertical concrete struts or posts at corner angles, suffered out-of-plane collapse as shown in Fig. 3.5. Moreover, all the problems described above, aggravate and increase potentially, the out-of-plane collapse of masonry wall panels.

Figure 3.5. Collapse of unconfined masonry panels

In-plane damage is inevitable when masonry infills and enclosure walls contribute to the overall response of the building to seismic action. In Fig. 3.6 is shown typical in-plane damage and short column mechanism due to the presence of openings in masonry enclosure walls.

Figure 3.6. In plane damage of masonry walls

4. PERFORMANCE REQUIREMENTS AND COMPLINACE CRITERIA

4.1 Design codes and International recommendations

Being aware of the importance of infill masonry elements in the behaviour of RC buildings in the last few years the new codes have included some provisions regarding the consideration of the infills and their influence on the structural response, namely Eurocode 8 [CEN, 2004], Eurocode 6 [CEN, 2005], FEMA 310 [1998], and ATC-40 [1996].

For example, the Eurocode 8 [CEN, 2004], include general recommendation for non-structural elements, acknowledging that, in case of failure, are a risk to human life or affect the main structure of the building and should be verified to resist the design seismic action. Eurocode 8 [CEN, 2004] also refers to the safety verification of the non-structural elements, as well as their connections and attachments or anchorages, during the design, considering that the local transmission of actions to the structure by the fastening of non-structural elements and their influence on the structural behaviour should be taken into account. For the particular case of the infill masonry panels, in particular if the masonry infills are in contact with the frame (i.e. without special separation joints), but without structural connection to it (through ties, belts, posts or shear connectors) can affect the ductility class of the structure. In particular for panels that might be vulnerable to out-of-plane failure, the provision of ties can reduce the hazard of falling masonry. For the structural systems belonging to all ductility classes, DCL, M or H, appropriate measures should be taken to avoid brittle failure and premature disintegration of the infill walls (in particular of masonry panels with openings or of friable materials), as well as the partial or total out-of-plane collapse of slender masonry panels and particular attention should be paid to masonry panels with a slenderness ratio of greater than 15.

The ATC-40 [1996] acknowledges the cost and disruption of bringing non-structural systems in older buildings into conformance with current codes is high, although these systems have suffered considerable damage in past earthquakes, the damage has generally not caused extensive hazardous conditions. Non-structural systems, therefore, have not been reviewed in most retrofits to date. However, large, highly vulnerable elements have often been investigated for their potential to fall and cause injury. The criteria used to determine the need to investigate is unclear, but vulnerability-to-damage and the extent of occupant-exposure are initial considerations. The extent of retrofit is often a cost consideration. The non-structural performance level of hazards reduced is intended to include only major hazards and encourage cost effective risk reduction.

FEMA 310 [1998] in the basic non-structural component checklist for the building evaluation define that non-structural components namely partitions masonry veneers, cladding and parapets, should respect the compliance criteria in accordance to seismic zoning (fixtures, spacing's and anchoring) and the evaluation procedure should be based on the forces and drift limits.

The definition of limit states for infill masonry panels can be directly related to the inter-storey drift demand. Based on the equivalent strut model, Magenes and Pampanin [2004] have proposed drift values for the damage level of a masonry infill panel corresponding to a certain limit state, depending on the axial deformation. For example, an inter-storey drift value in the range of 0.4%-1.0% can be associated to the infill panel's failure.

The FEMA-306 [1999] and FEMA-307 [1999] documents provide also reference values of inter-storey drift ratios for RC buildings with infill masonry panels. The drift limits proposed differ with the type of masonry, from 1.5% for brick masonry to 2.5% for ungrouted concrete block masonry. In these documents are also indicated a drift reference value of 0.25% for the initiation of diagonal cracking [Bell and Davidson, 2004]. Other authors recommended inter-storey drifts to be considered for the serviceability check ranging from 0.2% to 0.5%, depending on the type of partitions. Values around 0.2% are recommended for brick masonry infills in contact with the surrounding frame [Valiasis and Stylianidis, 1989] whereas 0.5% is more appropriate for plywood, plaster, gypsum and similar light panels [Freeman, 1977].

4.2 Improving integrity and overall stability

In what concerns to the improvement of the integrity and overall stability of the masonry infill panels the appropriate measures are proposed to improve in-plane and out-of-plane integrity and the performance behaviour under seismic action, as well reduce the risk of premature disintegration of walls namely: *i*) wall ties, *ii*) anchors, fasteners and shear connectors; *iii*) mortar bed joint reinforcement, *iv*) Dimensions and minimal width (slenderness ratio, overlapping), *v*) complementary units, *vi*) shelf angles and *vii*) posts, belts; among others.

In fact even the Eurocode 8 [CEN, 2004] points out examples of measures in accordance with ductility classes, to improve both in-plane and out-of-plane integrity and behaviour: inclusion of light wire meshes well anchored on one face of the wall, wall ties fixed to the columns and cast into the bedding planes of the masonry, and concrete posts and belts across the panels and through the full thickness of the wall. If there are large openings or perforations in any of the infill panels, their edges should be trimmed with belts and posts. The Eurocode 6 [CEN, 2005] in the recommendation for the connection between cavity walls impose that the two leaves of a cavity wall shall be effectively tied together if the number of wall ties connecting together the two leaves of a cavity wall should be not less than 2 ties/m² of the cavity wall.

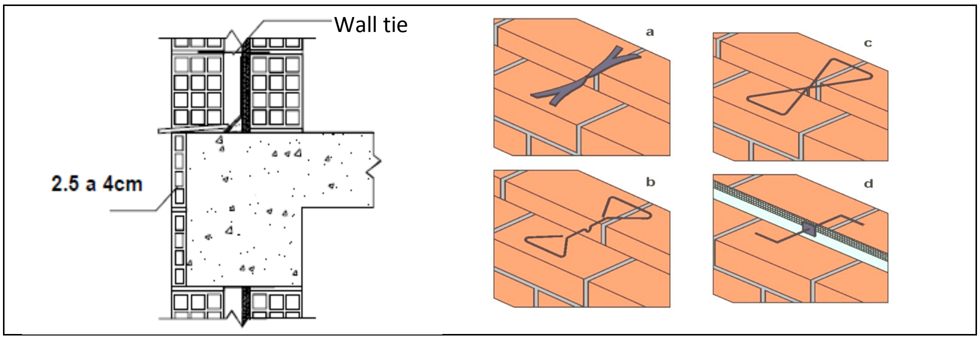

Figure 4.1. Wall ties- examples of wall ties connecting two leaves of a cavity wall

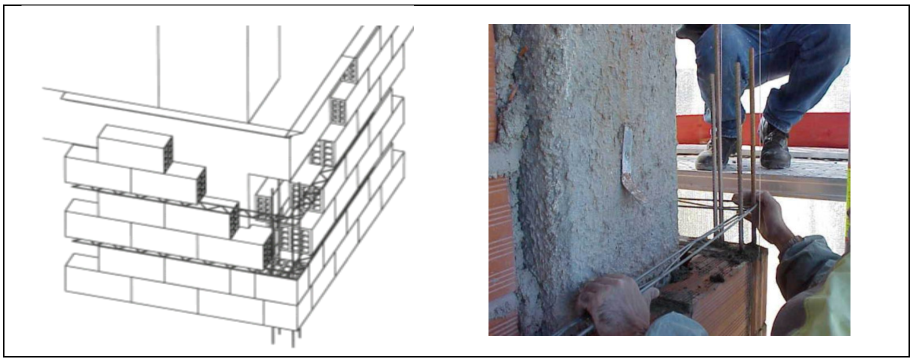

Figure 4.2. Wire welded horizontal reinforcement

5. CONCLUSIONS

From the Abruzzo Earthquake technical mission, it is quite notorious that non-loadbearing masonry design and its execution are insufficiently supported on a sound technological knowledge, particularly in what concerns external enclosure detailing and execution, used to enhance thermal performance. The external correction of thermal bridges, using clay brick walls, is still a construction issue after so many years, due to the insufficient technological knowledge on this matter. Non-loadbearing masonry design and verification must be promoted, particularly in what concerns adequate detailing of singular points. The encouragement of the use of methods of simplified design and calculus to evaluate stresses and movements due to various factors (wind and seismic action, thermal and moisture expansion) is fundamental to identify problems and expected behaviour. Therefore it is quite important to survey new constructions – where external correction of thermal bridges was applied – to learn more about their behaviour and to initiate the eventual retrofitting actions. Special attention should be given for walls of great extension. It is necessary to make good workmanship practice by the use of anchors, fasteners, joint reinforcement, shelf angles and wall ties connecting internal and external leaves to a common practice, particularly in partially supported walls. All the normative documents and design guidelines identified and consulted must give more prescriptive solutions for non load-bearing walls with the indication of validated and tested solutions is urgent.

ACKNOWLEDGEMENTS

The authors thank the entire technical team form the University of Aveiro and the Faculty of Engineering of the University of Porto. They also would like to thank to the local Italian Civil Protection Corps and firefighters and Prof. Giorgio Monti from the University of Rome for all their help an for granting accessibility to the affected areas.

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